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15 in. × 15 in.; (2) the 12 in. × 10 in. as a check upon false nebulæ and false stars, both upon paper with gelatine surface; (3) the triangle plates upon writing paper, and for this reason, besides being a second check upon faults in film, they should be a valuable help to workers in special branches of stellar work. A double-star worker, for instance, could number all known double stars according to the several catalogues, Σ 1004, B 191, I 34, and so on. The same with variables, nebulæ, &c. The expense of such publication would, however, be so serious that I must wait until better times in South Africa for a millionaire to help me with the cash, and in the meantime I propose to print photographically about five copies for public institutions. Any printing, whether photographic or mechanical, will, however, be absolutely *untouched*, and will show all faults, scratches, &c. It seems to me that a single interference of only one spot in a thousand plates would cast a doubt upon the pictorial integrity of any given region.

To record my sense of thanks to Sir David Gill for his kindness in allotting me a splendid site, and for his ever-kindly help and advice, is a great pleasure. Each one of the staff of the Royal Observatory at Cape Town has done his best to render the work as easy and as agreeable as possible.

Professor Barnard has had a 10-inch lens and mount made in America, the lens by Brashear and the mount by Warner & Swasey. It will be interesting to compare the two instruments. I have reason to think that of the two his will work upon a rather smaller field, and that his lens will be more rapid. I do not know the direction in which he proposes to work, nor do I know the scale.

In these days of many observatories in Great Britain, understaffed though they may be; of many more on the continent of Europe, supplied liberally with Government funds; and of still more in America, where wealthy citizens give large sums to build, house, and endow instruments of record size, it may seem difficult to find an unoccupied field of research. That there are such fields, however, is certain, and among them it seems likely that many will be found in that domain which contains the secrets of the structure of the universe.

Description of the Lenses. By H. Dennis Taylor.

Mr. Franklin-Adams has asked me to give a condensed description of his 10-inch aperture Cooke lens, with a short explanation of the theory of its construction.

It is a particular case of the Cooke photographic lens modified for celestial purposes. The essential aim of the Cooke lenses was to obtain a flat image substantially free from astigmatism, besides being rectilinear and achromatic, with the minimum number of lenses possible. This result was obtained with only three simple lenses, two outer positive lenses and an inner

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negative lens, which latter had to perform simultaneously the following functions:

1st. To correct the spherical aberration of the two positive lenses, on the axis as well as obliquely.

2nd. To correct the chromatic aberration of the two positive lenses, not only along the axis but obliquely, and also be so placed in position as to cause the final images in various colours to be of the same size and free from curvilinear distortion.

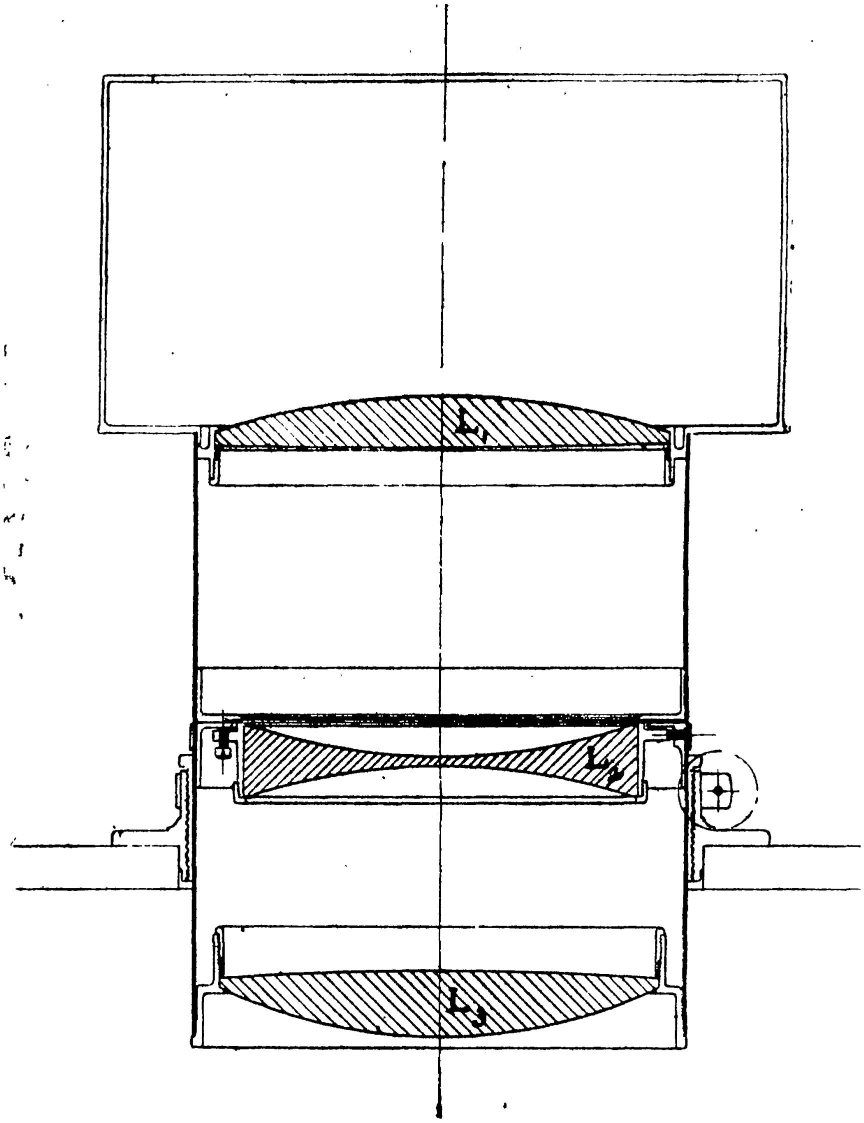

Fig. 1.

3rd. To correct the curvature of image of the two positive lenses, if possible both in primary and secondary sections of the same oblique pencil simultaneously, so as to bring about a final flat image free from astigmatism.

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4th. To correct the coma, if any, produced in the oblique pencils by the two positive lenses.

All the above corrections may be carried out simultaneously, although very much interlocked, by a suitable choice of materials, relative powers, and shapes of the lenses, together with suitable separations. A longitudinal section of the complete lens is given in fig. 1.

Spherical Aberration.

It is obvious that we have the power of varying the collective spherical aberration of the two positive lenses between the extreme values $(a+a)$ and 2^3a or $8a$ for any constant aperture, combined power, and separation between the two positive lenses. If they are of equal powers and equal aberrations we have the sum of both aberrations or $(a+a)$, whereas if the power of one lens is about vanished and the power of the other is correspondingly about doubled then the collective aberrations become $(0+8a)$. Thus the collective spherical aberration is capable of being varied to suit any desired negative lens.

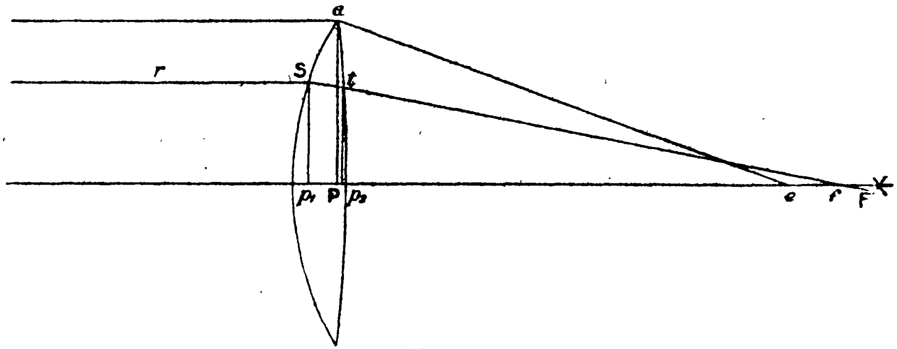

FIG. 2.

There remains for lenses of large relative aperture the question of zonal aberration, a defect of no particular consequence for camera lenses, but of immense importance in the case of lenses for celestial photography which are required to give the sharpest possible images of stars.

Fig. 2 represents a double convex lens on which falls an axial pencil of parallel or divergent rays.

Let the curves be carried out to a sharp edge *a*, and let the semi-aperature *a*P (*a*—P being perpendicular to the axis) be called A. Let a ray be traced through the sharp edge. It meets with a certain amount of spherical aberration, which is a function of A^2, and is refracted to the point *e* considerably nearer to the lens than F, the point where the ultimate axial rays come to focus. Then *e*—F is the longitudinal spherical aberration. Let an intermediate ray *r*—*s*—*t*—*f* be considered. It strikes the first surface at *s* at a perpendicular distance $s-p_1$ $(=y)_1$ from the axis and it meets with a certain amount of spherical aberration, which is a function of $y_1{}^2$. After refraction the ray converges

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towards the axis, and after traversing the thickness of glass $s-t$ it meets the second surface at t nearer the axis, so that $t \ldots p_2$ or y_2 is appreciably less than y_1. It is this disparity between the two y's at the two surfaces at positions in the lens between the axis and the sharp edge which gives rise to zonal aberration.

If the aberration of such a lens is examined by projecting the sections of the cone of rays on to a screen or by an eyepiece then the zone of aberration is so disguised by the much greater general aberration as to be invisible; but supposing the general aberration is neutralised by the general aberration of a negative lens, then the zonal aberration shows up, and we get an imperfect focus; for while we may get the extreme edge ray to focus at the same point as the ultimate axial rays, yet there is a zone in the lens from which the rays cut the axis at a point considerably inside of the focus for edge and centre rays. If a section of the cone of rays be taken at a point a little inside of that focus the patch of light takes the form of a disc with a bright zone about half-way between the centre and the edge, while outside of the focus the edge and centre of the disc of light are the brightest. If Y stands for either y_1 or y_2 then the zone of aberration is a function of $\mathrm{Y}^2(\mathrm{A}^2-\mathrm{Y}^2)$ into the spherical aberration of the first surface, and obviously is at a maximum when $\mathrm{A}^2 = 2\mathrm{Y}^2$, which occurs round a zone of the lens where the thickness is half of the central thickness, the radius of the zone being $\frac{\mathrm{A}}{\sqrt{2}}$. It is obvious then, that if we could always use lenses whose thicknesses at the edges were more than half of their central thicknesses, their aperture would always be inside their zones of aberration, and the latter be practically got rid of; but large thicknesses are so objectionable on account of weight and light absorption, especially in the case of large lenses for stellar photography, that it is scarcely to be thought of, and other methods have to be devised. We have to deal with the case of the rays impinging upon the first lens being parallel, and those impinging upon the third lens being divergent. In the case of the first lens the zone of aberration is a function of the aberration of the first surface, and (supposing shape of the lens is kept constant) that aberration is a function of $\left(\frac{1}{r}\right)^3\left(\frac{1}{\mathrm{F}}\right)^2$, or the cube of the reciprocal of the radius of curvature into the square of the focal power.

Therefore the zone of aberration of the first lens can be enormously reduced by keeping down its power, while, since in the back lens the rays traverse its substance more nearly in a state of parallelism than in the case of the first lens, an increase in the power of the back lens balancing the decrease in power of the front lens does not augment the zone of aberration of the back lens in anything like the same degree. For this reason the power of the back lens was made preponderant. In the first model the two positive lenses were equal in power, and the zone of aberration was so bad that the lens was practically useless for

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stellar work in large sizes, and at any aperture over $\frac{F}{5}$, nor could the zone of aberration be got rid of by special figuring, whereas the present arrangement of making the power of the back lens about $1\frac{1}{2}$ times the power of the front lens so reduces the zone of aberration as to render it possible to get rid of it entirely by special retouching; a somewhat troublesome but quite practicable process. In the case of negative lenses which grow thicker as the centre is left and have no sharp edge it is obvious that zones of aberration do not arise.

Of course the state of the chromatic correction of the final image along the axis is simply a matter of the mutual adjustment of the relative dispersive powers of the positive and negative lenses.

But whether or not the oblique image of stars shall also be achromatic, or whether they shall be drawn out into spectra, pointing to the centre of the field, depends upon the negative lens being placed at a certain position between the two positive lenses. Should this condition be fulfilled then the other highly important condition of freedom from distortion or rectilinearity is simultaneously attained.

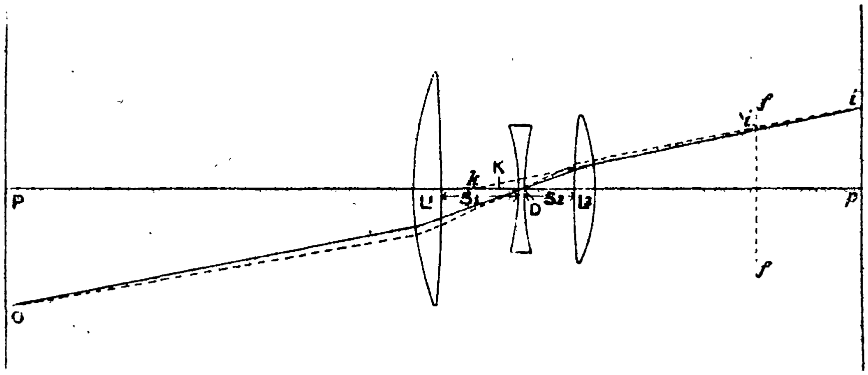

Fig. 3.

The diagram fig. 3 shows one of these lenses considered as reducing or copying in the ratio 3 to 2. OP is the original and *ip* the image, O being a particular point in OP and *i* its image. As the two positive lenses are of the same shape, but turned in opposite ways, and the distance $PL_1 : pL_2 :: F_1 : F_2$, and we place the diaphragm point at D, such that $L_1D : L_2D :: F_1 : F_2$ also; then it is obvious, without stating the formulæ for distortion (which fully confirm this case), that all is symmetrical on each side of D and $ip : OP :: L_2p : L_1P$ exactly. Hence there is no distortion, and the lens gives a rectilinear image. Moreover, all the variously coloured oblique principal rays from O will pass through D, although traversing each lens L_1 and L_2 at different distances from the axis. For instance, the solid line shows the path of a yellow principal ray from O, while the dotted line shows the path of a blue principal ray from O. If, therefore, the centre of the

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negative lens, of properly chosen dispersive power, is also placed at D, the intercrossing or diaphragm point, then we secure that the various colours come to final focus in the same plane, while at the same time the conditions of oblique achromatism also hold good, for the variously coloured principal rays go straight through the centre of the negative lens as if it were not there, and traverse L_1 and L_3 at heights from the axis always proportionate to their focal lengths. Hence perfect symmetry prevails. But supposing the original OP is removed to a much greater distance or infinitely far off, and *p* moves up towards the principal focal plan *ff*, then the conditions of oblique achromatism for the image of the point O no longer strictly hold good. It is obvious that the blue image of O at *i* will fall a little further away from the axis than the yellow image at the same time that positive distortion will arise. For the image of the diaphragm point D as viewed through the back lens L_2 is subject to spherical aberration, the principal ray or line of projection *ik* radiating from *k*, whereas the image point of D formed by L_2 would be at K were it not for its spherical aberration. Thus, *k*—K is the longitudinal spherical aberration of L_2. Therefore the line of projection *k*—*i* strikes the principal focal plane *f*—*f* too far from the axis, and there is positive or pincushion distortion of the images of straight lines. In order to correct this it is necessary to move the negative lens nearer to L_1 by such an amount as is necessary to again make the various coloured rays from O or a star all strike the principal focal plane *f*—*f* at the same distance from the axis, when it will be found that the lens will also become quite rectilinear again. In the case of Mr. Franklin-Adams's lens the amount of movement required is about ·39 inch, or 3 per cent. of the whole separations. While in certain other combinations of separated simple lenses, such as the Huygenian eyepiece, and four lens-erecting eyepiece, the conditions of freedom from distortion and oblique achromatism are more or less independent of one another in these Cooke lenses; provided that the two positive lenses are of similar but reversed shapes, the two conditions of rectilinearity and oblique achromatism are necessarily simultaneously attained.

The actual state of colour correction in these lenses as designed for stellar work is not such as to bring the actinic blue rays about G̀ and the most luminous D rays to the same focus as in the case of camera lenses, but to bring the most highly actinic blue rays on the F side of G̀ to the minimum, and therefore most intense focus, the most luminous yellow green and yellow rays being refracted to foci considerably beyond, and thus the most distinct image from a purely photographic point of view is obtained at the sacrifice of the visual distinctness. The two positive lenses are made of heavy barium silicate crown, having a refractive index of about 1·57 for the D ray, and the negative lens of flint glass having a refractive index of about 1·623 for the D ray.

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Astigmatism and Flatness of Field.

3. The means whereby flatness of field combined with almost complete absence of astigmatism is attained really constitutes the most novel feature in the construction of these lenses.

If F = the principal focal length of any thin lens whatever, positive or negative, μ = its refractive index, and ϕ the angle of obliquity of any pencil of rays traversing the lens centrally, U the axial distance from the lens of any plane object placed perpendicular to the axis, and V the corresponding conjugate distance of the image from the lens, and y = the semi-aperture of the pencil when it traverses the lens, then

$$\frac{1}{V}=\frac{1}{F}-\frac{1}{U}+\frac{1}{8F^3}\omega y^2+\frac{\tan^2\phi}{2F}\cdot\frac{3\mu+1}{\mu}$$

wherein $\frac{1}{8F^3}\omega y^2$ = the spherical aberration to which all the pencils are subject and $\frac{\tan^2\phi}{2F}\cdot\frac{3\mu+1}{\mu}$ is the error of curvature of image as formed by the rays in the primary plane of the oblique pencil or in that plane containing the principal or central ray of the oblique pencil and the optic axis. Whereas the error of curvature for rays in the secondary plane of the same pencil or the plane at right angles to the former and also containing the principal ray is $\frac{\tan^2\phi}{2F}\cdot\frac{\mu+1}{\mu}$.

Thus the two curvature errors are

$$\frac{\tan^2\phi}{2F}\cdot\frac{3\mu+1}{\mu}\text{ and }\frac{\tan^2\phi}{2F}\cdot\frac{\mu+1}{\mu}$$

in the two planes, and, if $\mu = 1\cdot5$, are in the ratio 5·5 to 2·5 or 2·2 to 1, while their difference is $\frac{\tan^2\phi}{F}$ simply, which represents the astigmatic error of the lens. Thus the astigmatism depends solely upon the obliquity and the power of the lens and nothing else, while the two curvature errors depend also upon the refractive index, but are independent of U or V.

More than fifty years ago Petzval promulgated his now well-known theorem to the effect that if a system of thin positive and negative lenses combined in contact, and so arranged as to give a final image free from astigmatism away from the axis, then the image, if anastigmatic or free from astigmatism, will be curved to a radius whose reciprocal value is equal to $\Sigma\frac{1}{P\mu}-\Sigma\frac{1}{N.M}$ wherein $\Sigma\frac{1}{P}$ is the sum of the powers of the positive lenses and μ

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their refractive index, and $\Sigma\frac{1}{N}$ is the sum of the powers of the negative lenses and M their refractive index. Supposing $\mu = M$; then obviously, if $\Sigma\frac{1}{P} = \Sigma\frac{1}{N}$, then the reciprocal value of the radius of curvature of the final anastigmatic image becomes zero, that is, the image is flat as well as free from astigmatism. But, unfortunately, as the focal powers of the negative lenses would in that case completely neutralise the focal powers of the positive lenses, there could be no real image. But if the refractive index for the positive lenses would be made higher than that for the negative lenses, which is contrary to the usual state of things, and in Petzval's day not feasible consistently with achromatism, then obviously the above formula equates to zero when $\Sigma\frac{1}{P} = \Sigma\frac{1}{N}\frac{\mu}{M}$ which leaves the powers of the positive lenses in excess, so that the combinations will yield an actual image. Petzval did not fully make known how he arrived at his theorem, nor did he state the conditions under which the oblique pencils of rays would have to traverse the lens system in order to form an anastigmatic image on a flat surface. As a matter of fact, if the Petzval condition is fulfilled in a system of thin lenses in contact having $\mu = M$ and having the diaphragm point at their centre, so that the oblique pencils all traverse the *centre* of the system, then the final curvature of image for rays in primary sections of the oblique pencils is given by $\Sigma\frac{1}{P}\frac{\tan^2\phi}{2}\frac{3(\mu-M)}{\mu}$, and for rays in secondary planes by $\Sigma\frac{1}{P}\frac{\tan^2\phi}{2}\cdot\frac{\mu-M}{\mu}$, that is, the two errors are in the ratio 3 to 1 instead of the usual 2.2 to 1 or so in the case of simple lenses. What is now further required in order to uncurve both these curved images and throw them back simultaneously on to the plane passing through the axial focus is that the lenses must be given certain shapes, and that the oblique pencils of light must be constrained to pass *eccentrically* through the system. This latter condition is secured by placing a circular aperture, considerably smaller than the lens aperture, at some distance either behind or in front of the system. The oblique pencils of rays are thus compelled to traverse the system eccentrically and then become subject to further corrections which I call diaphragm corrections. It can be proved that any diaphragm correction equal to + or −1 affecting the rays in secondary sections of oblique pencils is invariably accompanied by diaphragm corrections equal to + or −3 affecting rays in primary sections of the same pencils. Therefore by suitable diaphragm corrections introduced into any contact system of positive lenses of high refractive index combined with negative lenses of low refractive index fulfilling the formula $\Sigma\frac{1}{P\mu} - \Sigma\frac{1}{NM} = 0$ we can get the image formed by

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secondary rays (of curvature = 1), and the image formed by primary rays (of curvature = 3) simultaneously thrown back upon the plane passing through the final axial focus, and thus obtain a positive image that is both flat and free from astigmatism.

Supposing we confine our attention to combinations of two simple thin positive lenses and one simple thin negative lens placed between and in contact in accordance with the above conditions we may go further than Petzval did, and consider what will happen, supposing the positive lenses are more and more separated from the negative lens. When in contact the power of the combinations on parallel rays is simply $\frac{1}{P_1}-\frac{1}{N}+\frac{1}{P_2}$; but it can be shown that when separated the power of the combinations becomes

$$\frac{1}{P_1}-\frac{1}{N}+\frac{1}{P_2}+\left\{\frac{S_1(P_2-N)+S_2(P_1-N)-S_1S_2}{P_1NP_2}\right\}$$

in which formula S_1 stands for the separation between first lens and negative lens, and S_2 the separation between the back positive lens and the negative lens.

The formula in brackets is the increment to the power due to separation alone.

Now while the power of a simple lens inevitably carries with it the proportional curvature errors

$$\frac{\tan^2\phi}{2F}\cdot\frac{3\mu+1}{\mu} \text{ and } \frac{\tan^2\phi}{2F}\cdot\frac{\mu+1}{\mu}$$

on the other hand it can be proved that the great increment to power brought about by separation in these triplets does *not* carry with it any curvature errors whatever, and is an unqualified gain. A contact triplet combination of the power 1 and aperture $\frac{F}{16}$ may, when separated, give a power equal to 2 or 3, with respective apertures of $\frac{F}{8}$ or $\frac{F}{5\frac{1}{3}}$, while its image will under certain conditions remain flat and free from astigmatism if the equation $\frac{1}{P_1\mu}-\frac{1}{N\,M}+\frac{1}{P_2\mu}=0$ is fulfilled. The next question that occurs is, supposing this equation, which we may call the Petzval condition, is not strictly fulfilled, either in that the negative lens is of a less power than the equation specifies, or that its refractive index is higher instead of lower than that of the positive lenses, as is the case in this Cooke lens for stellar photography; then can the image still be got sufficiently free from astigmatism if flat? The answer is in the affirmative. For although in the case of a contact combination giving a flat mean image, there is sure to be more or less considerable astig-

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matism should the Petzval condition be departed from, yet since the resultant focal power is very largely increased by separation of the lenses, these errors are relatively decreased. If the focal power is doubled or trebled by separation, then the errors consequent upon not fulfilling the Petzval condition are relatively reduced to $\frac{1}{2}$ or $\frac{1}{3}$ respectively.

There are as often as not practical difficulties in the way of strictly following the Petzval condition, so that a method of construction which enables one, as it were, to drown the errors due to its non-fulfilment, and therefore becomes to a large extent independent of it, has much to recommend it. As in Mr. Franklin-Adams's type of lens the refractive index of the two positive lenses is 1·5853 for the G̀ ray, and that of the negative lens about 1·64615, then the Petzval condition demands that the power of the negative lens should be $\frac{1\cdot646}{1\cdot575}$, or 1·04 times the sum of the powers of the two positive lenses. As a matter of fact it is only about ·9475, a deviation of ·09, or 9 per cent. from the Petzval condition, which would be fatal in the case of a contact combination of lenses, but is of vanishing importance in this widely separated combination, 86 per cent. of whose equivalent focal power is due solely to separation, and whose residual astigmatism for the G̀ ray is thus reduced to an exceedingly small amount, namely, to one-seventh part.

For the *total* actual power of the lens $= \frac{1}{44\cdot6} = \cdot0224$, while the sum of the powers of the three lenses $=$

$$\begin{array}{rl} +\cdot039305 & \text{for } L_1 \\ +\cdot058417 & \text{for } L_3 \\ \hline \cdot097722 & \\ -\cdot094545 & \text{for } L_2 \\ \hline +\cdot003177 & \text{total} \end{array}$$

Thus the actual power is seven times the simple sum of the powers of the constituent lenses, and therefore the astigmatic error as expressed by $\frac{1}{\mu P_1} - \frac{1}{MN} + \frac{1}{\mu P_2}$, wherein the Petzval condition is not fulfilled, is reduced or diluted seven times.

It is also obvious, since the power of the negative lens is so nearly equal to the sum of the powers of the positive lenses, that the mean curvature errors of the latter as expressed by $\frac{\tan^2 \phi}{2}\left(\frac{1}{P_1}+\frac{1}{P_2}\right)\frac{2\mu+1}{\mu}$ are almost completely neutralised by the corresponding opposite errors of the negative lens or

$$\frac{\tan^2 \phi}{2} \cdot \frac{1}{N} \cdot \frac{2M+1}{M}$$

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Anyway, the remaining positive curvature errors are so small (in this case only about 5 per cent.) compared to the total curvature errors of either the positive lenses or negative lens that any diaphragm corrections left in the system for correcting these residual curvature errors are also merely residual. Hence the lens may be described as composed of three simple lenses each of which is so shaped as to be about free from diaphragm corrections when the rays first incident on the first lens have a certain assigned degree of divergence. In this particular case the lenses are symmetrically disposed to two conjugate focal planes, one being at a distance from the front lens L_1, equal to $1\frac{1}{2}$ times the distance of the conjugate focus from the back lens L_3. Also the first separation S_1 is about $1\frac{1}{2}$ times the second separation S_2, and the diaphragm point is supposed to be at the centre of the negative lens. As the oblique pencils pass centrally through the negative lens, no appreciable diaphragm corrections arise in its case, whatever its shape may be, but the two positive lenses have to be so shaped that the presence of the diaphragm a long way behind L_1 and in front of L_3, causing the oblique rays to traverse those lenses eccentrically, shall have a disturbing effect equal to -5 per cent. of the natural mean curvature errors of the two lenses as expressed by

$$\frac{\tan^2\phi}{2}\left(\frac{1}{P_1}+\frac{1}{P_2}\right)\frac{2\mu+1}{\mu}$$

In other words, the diaphragm corrections of the two lenses are simultaneously approximately eliminated or reduced to nearly zero. It is almost the same thing as saying that the two positive lenses are so shaped as to be about free from coma under the conditions in question. Thus, the diaphragm corrections being about eliminated from the system under the above conditions, it can be shown that the system as a whole will remain about free from diaphragm corrections should the plane object presented to L_1 on the left be removed by an infinite distance. For slight outward coma will then arise in L_1, giving rise to positive diaphragm corrections, but outward coma will simultaneously arise in L_3, giving rise to negative diaphragm corrections neutralising the former, so that the final image will retain its flatness, while at the same time inward coma arises in the negative lens, which neutralises the outward coma of the two positive lenses.

Also in order to retain the oblique achromatism of the lens under the new conditions, the negative lens should be moved nearer to L_1, as we have seen before when dealing with the chromatic correction and rectilinearity of the lens. The amount of this axial traverse of the negative lens required between the symmetrical case of copying or reducing 3 to 2 and the case of photographing infinitely distant objects varies roughly as the cube of the separation between the two

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positive lenses, other things being equal, and in Mr. Franklin-Adams's 10-inch lens is actually about ·39 inch. The adjustments of a large lens of this type are necessarily of a very delicate nature, and means are provided both for tilting the negative lens in any direction with respect to the optic axis and also for moving it laterally in any direction parallel to itself. Perfect symmetry of field is thus more at command, and after that has been satisfactorily secured the negative lens is carefully fixed in position.

The actual photographs taken and exhibited by Mr. Franklin-Adams will sufficiently show the capabilities of the lens for stellar photography in cases where large regions of the sky are required to be depicted in one view.

1903 *July* 10.

Description of the Mount. By Alfred Taylor.

The mounting was designed to utilise two existing cameras with lenses of unequal sizes and focal lengths. Both cameras having to be in use at the same time, the results from one serving as a check on the other, perfect parallelism and sympathy of motion are of great importance. Rigidity in the mounting, with great ease of working, had therefore to be carefully kept in view in its construction.

The mounting is of the English type, there being no central pillar to interfere with a complete twelve hours' run for all positions of the telescope. This is an important factor where star photography is concerned. The polar axis consists of a cross-braced steel frame, square in section, the width at the middle being determined by a suitable spread of bearings to give length to the declination axis. Both ends of the polar axis run in double ball bearings, mounted in swivelling frames, which take the side thrust due to the inclination of the axis, while another ring of balls at the lower end takes the end thrust there. The swivelling frames much reduce the difficulty of adjusting the polar axis, and the risk of friction from error in alignment there would be with plain bearings. Ball bearings have been successfully adopted by T. Cooke & Sons for some time on equatorial mountings carrying telescopes anything over 6 inches in diameter, the reduction of friction and consequent ease of movement greatly conducing to regularity in running, the work required to be overcome by the driving clock being more uniform and considerably less than with plain bearings.

The hour-circle, tangent wheels for both axes, and declination circle are all of gun-metal.

The R.A. tangent wheel is 43 inches diameter, and has 1080 teeth. It is loose on its axis and can be clamped by a screw worked by bevel wheels and loose cords led conveniently near to the eye-ends of the guiding telescopes.

The hour-circle is 24 inches diameter, both edges divided on